

# **I. Partonic Equation of State in High-Energy Nuclear Collisions**

## **II. Neutrino Properties**

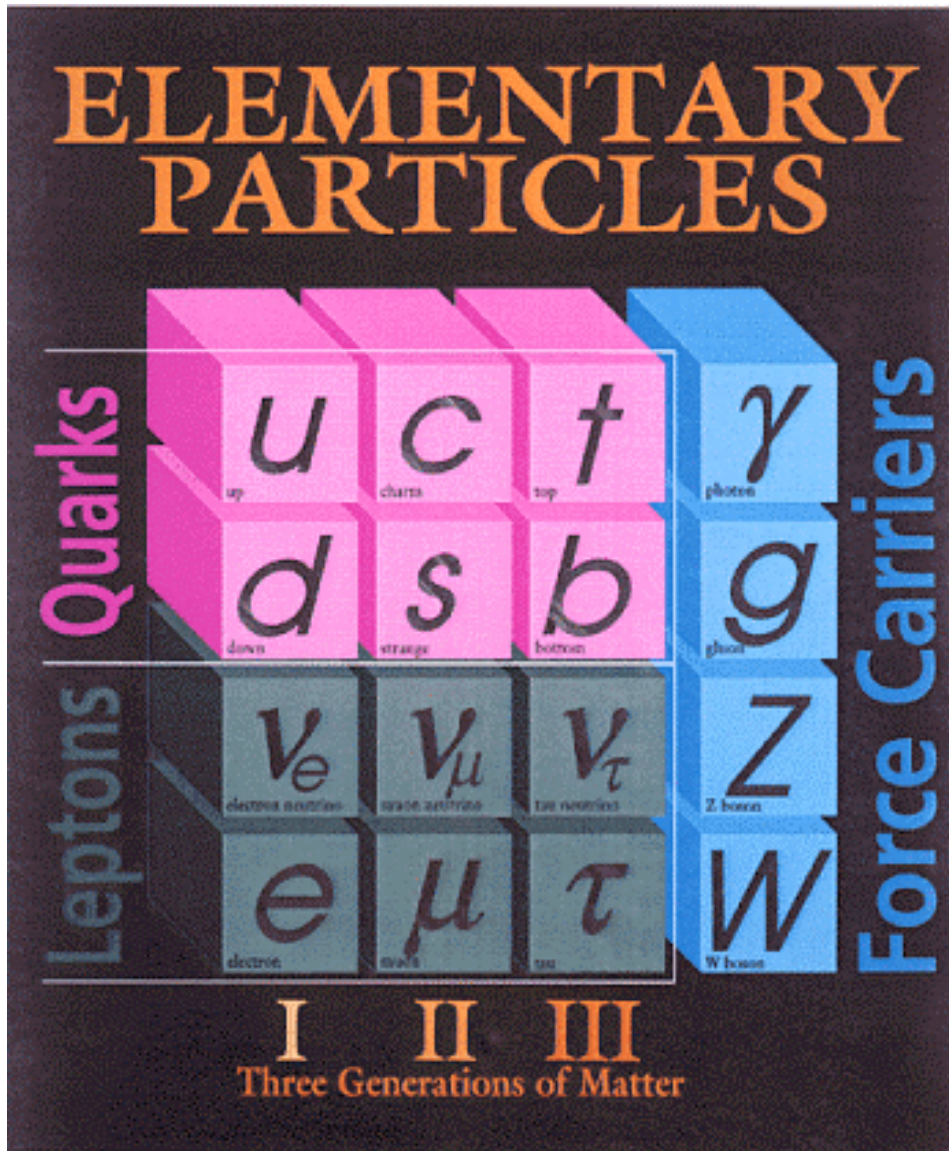
**Nu Xu**

*Nuclear Science Division  
Lawrence Berkeley National Laboratory*

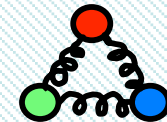
Email: [NXu@lbl.gov](mailto:NXu@lbl.gov)      Webpage: <http://www-rnc.lbl.gov/~nxu>

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# “Standard” Model

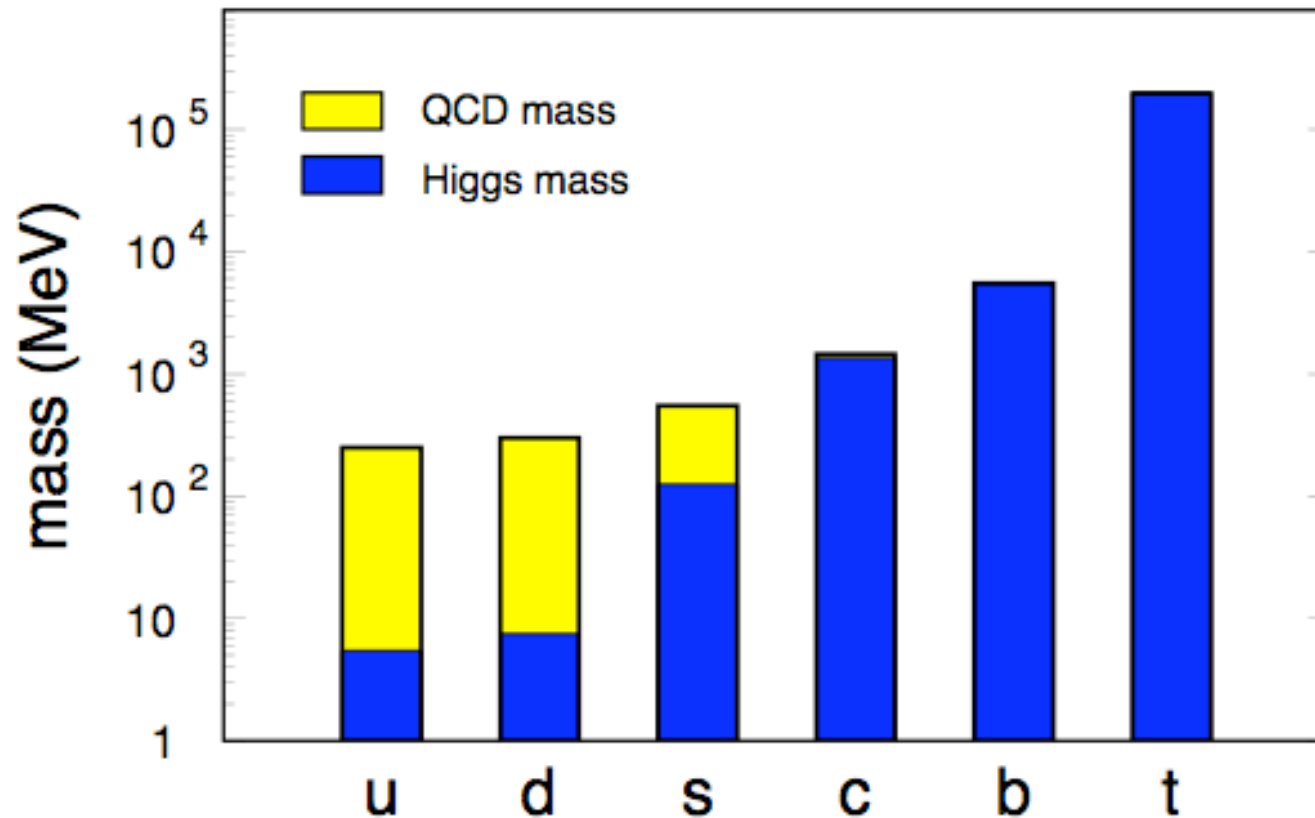


**Strong Interaction:** is understood to represent interactions between *quarks* and *gluons* as detailed by the theory of QCD. The strong force is the fundamental force mediated by gluons, acting upon quarks, antiquarks, and gluons themselves. Quarks and gluons are confined in colorless hadrons:



**Weak Interaction:** is one of the four fundamental forces of nature. It is most commonly seen in beta decay and the associated radioactivity. The weak nuclear force affects all *leptons* and *quarks*. It is the only force affecting *neutrinos*. It is about  $10^{13}$  time weaker than the strong force.

# The masses



Muller:  
nucl-th/0404015

- 1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
- 2) QCD mass: Chiral symmetry breaking. (constituent quark mass)

⇒ Strong interactions do not affect heavy-quark mass.

# Outline

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## **Search for Quark Gluon Plasma (QGP)**

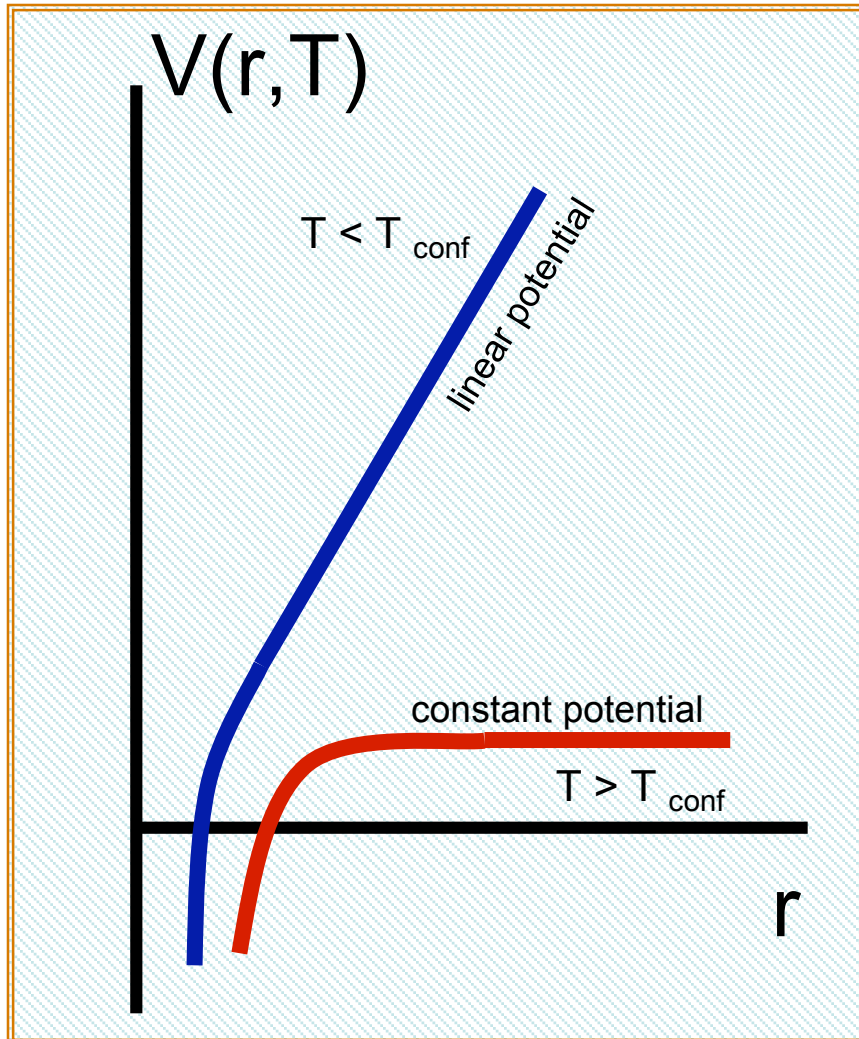
- History of the high-energy nuclear collisions
- Equation of state with parton degrees of freedom
- Recent progress in STAR at RHIC

## **Neutrino properties**

- Neutrino-less double beta decay
- The CUORE experiment at Gran Sasso



# QCD confinement potential



The potential between quarks is a function of distance. It also depends on the temperature.

1) At low temperature, the potential increases linearly with the distance between quarks

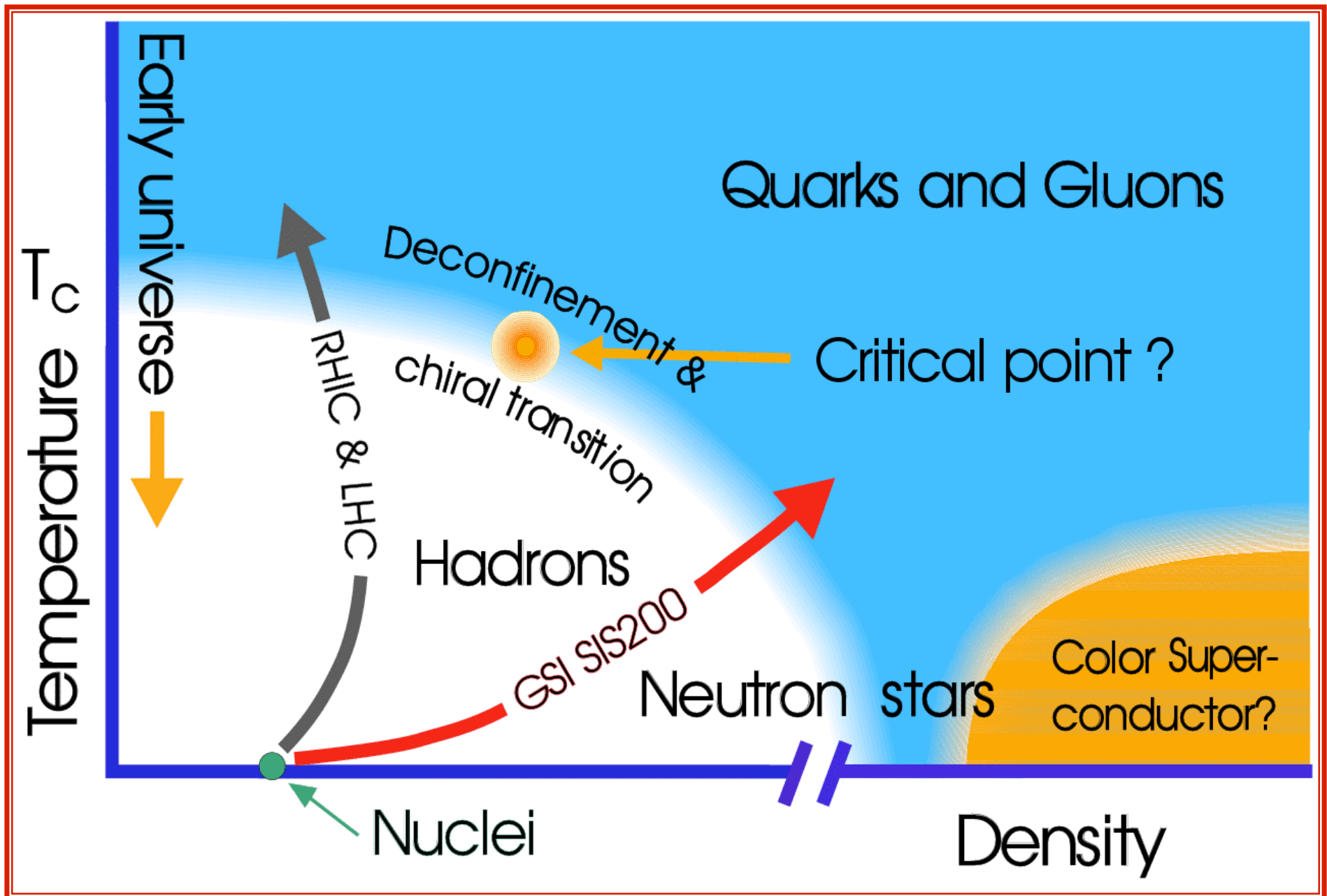
⇒ quarks are confined;

2) At high temperature, the confinement potential is 'melted'

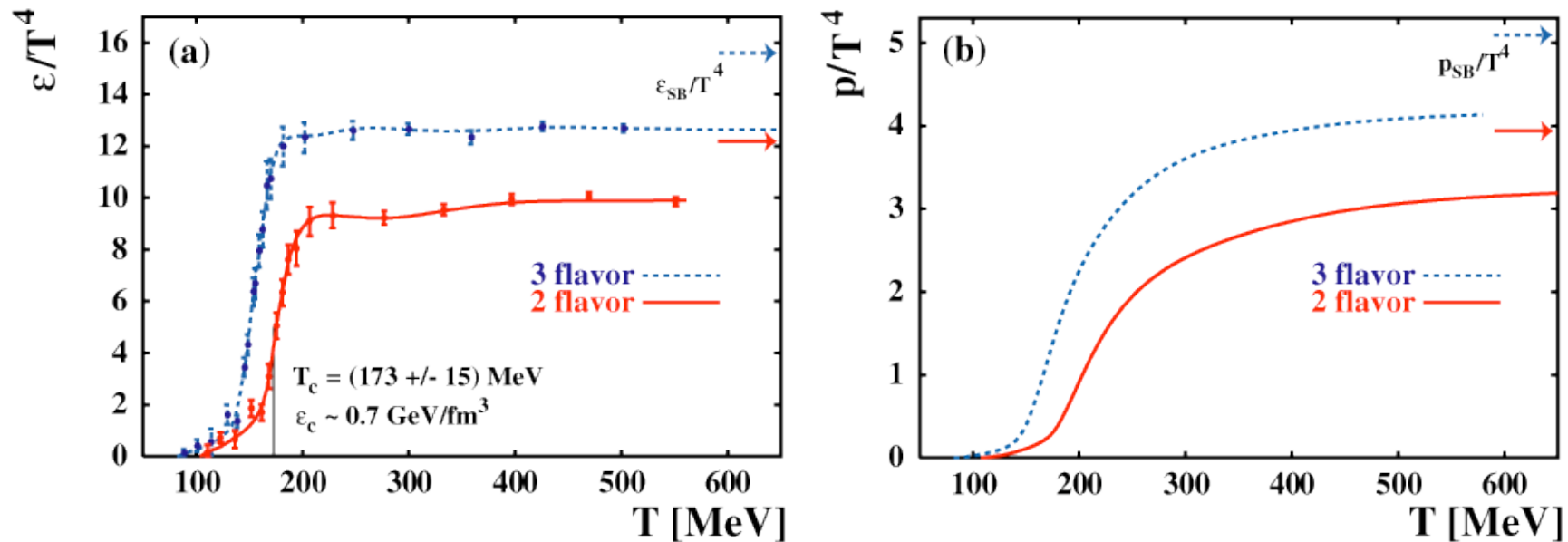
⇒ quarks are 'free' (larger than that from p+p collisions);

3) LGT calculation predicted a fast-cross over temperature

$T_c = 160 - 170 \text{ MeV}$ .



# Lattice QCD - the Equation of State



- (1) Large increase of degrees of freedom at  $T_c$  seen in quick change in energy density and pressure
- (2) Pressure gradient,  $dp/de$  generates collective flow

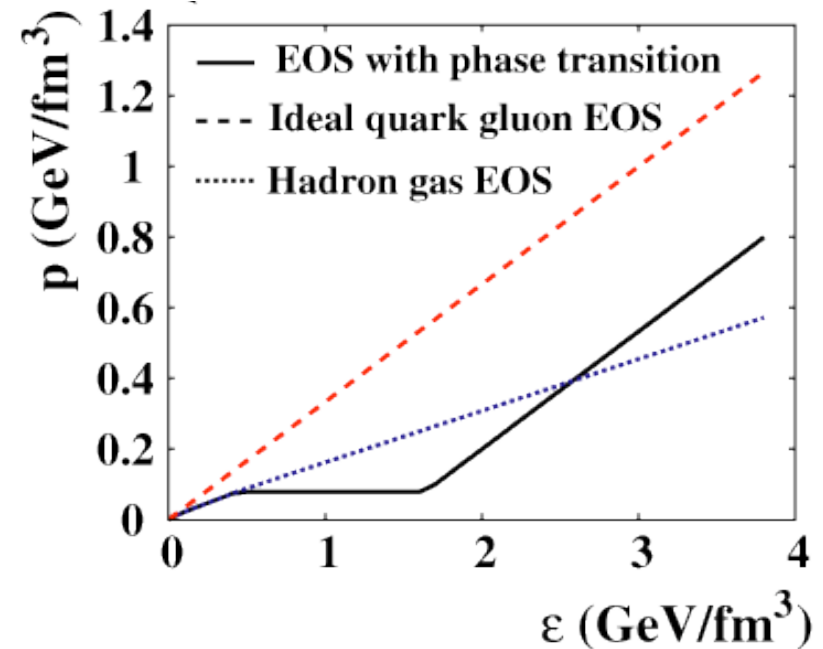
*F. Karsch and E. Laerman, hep-lat/0305025*

# Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \quad j^\mu(x) = n(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu} * p(x)$$



EOS - the system response to the changes of the thermal condition - is fixed by its  **$p$**  and  **$T(\varepsilon)$** .

## Equation of state:

- **EOS I**: relativistic ideal gas:  $p = \varepsilon/3$
- **EOS H**: resonance gas:  $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction:  
 $T_{\text{crit}} = 165 \text{ MeV}$ ,  $B^{1/4} = 0.23 \text{ GeV}$   
 $\varepsilon_{\text{lat}} = 1.15 \text{ GeV/fm}^3$

*P. Kolb et al., Phys. Rev. **C62**, 054909 (2000).*

# Physics goals at RHIC

**Identify and study the properties of matter with partonic degrees of freedom.**

**Penetrating probes**

- direct photons, leptons
- “jets” and heavy flavor

**Bulk probes**

- spectra,  $v_1$ ,  $v_2$  ...
- partonic collectivity
- fluctuations

Hydrodynamic  
Flow

=

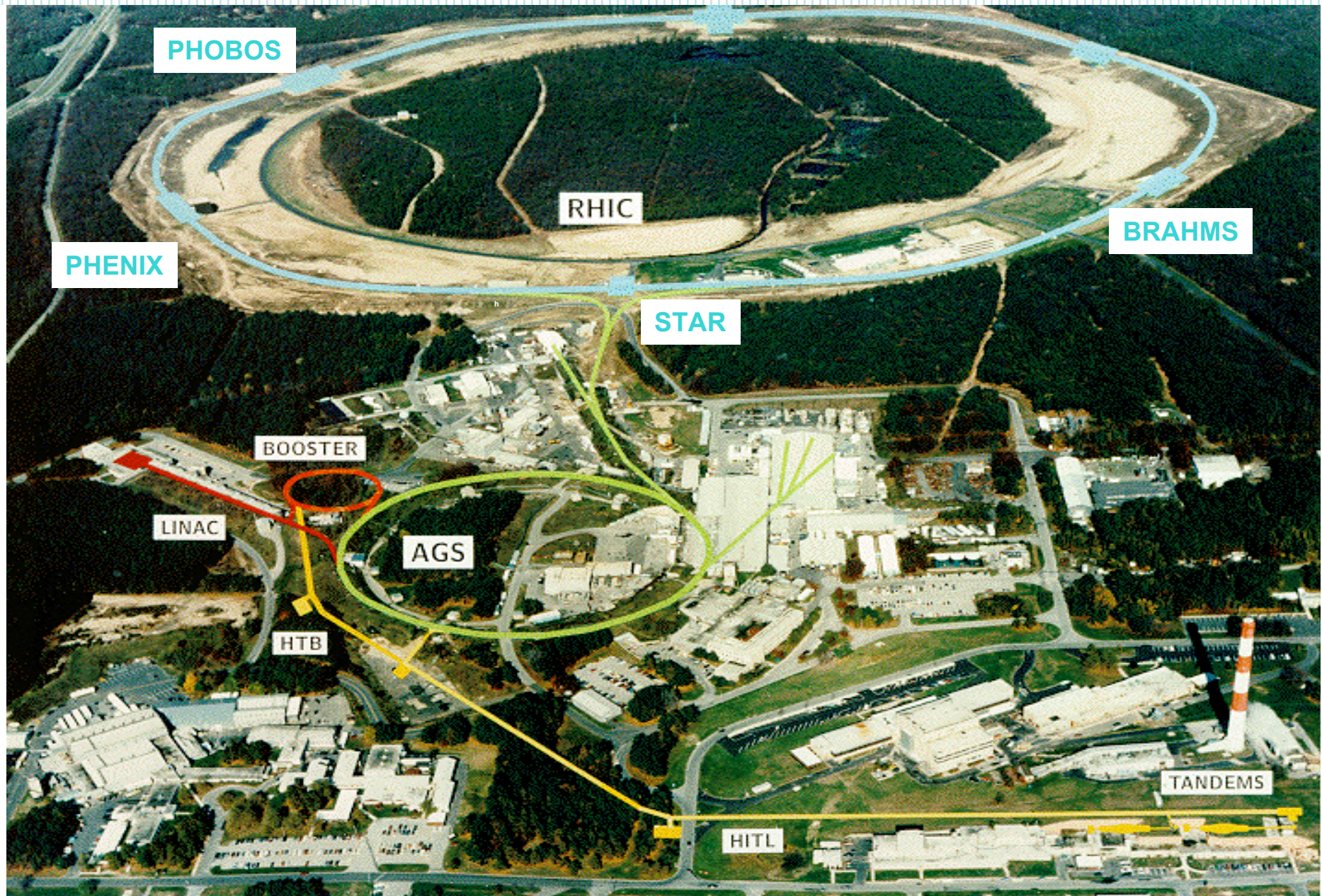
Collectivity

⊗

Local  
Thermalization



# RHIC @ Brookhaven National Laboratory



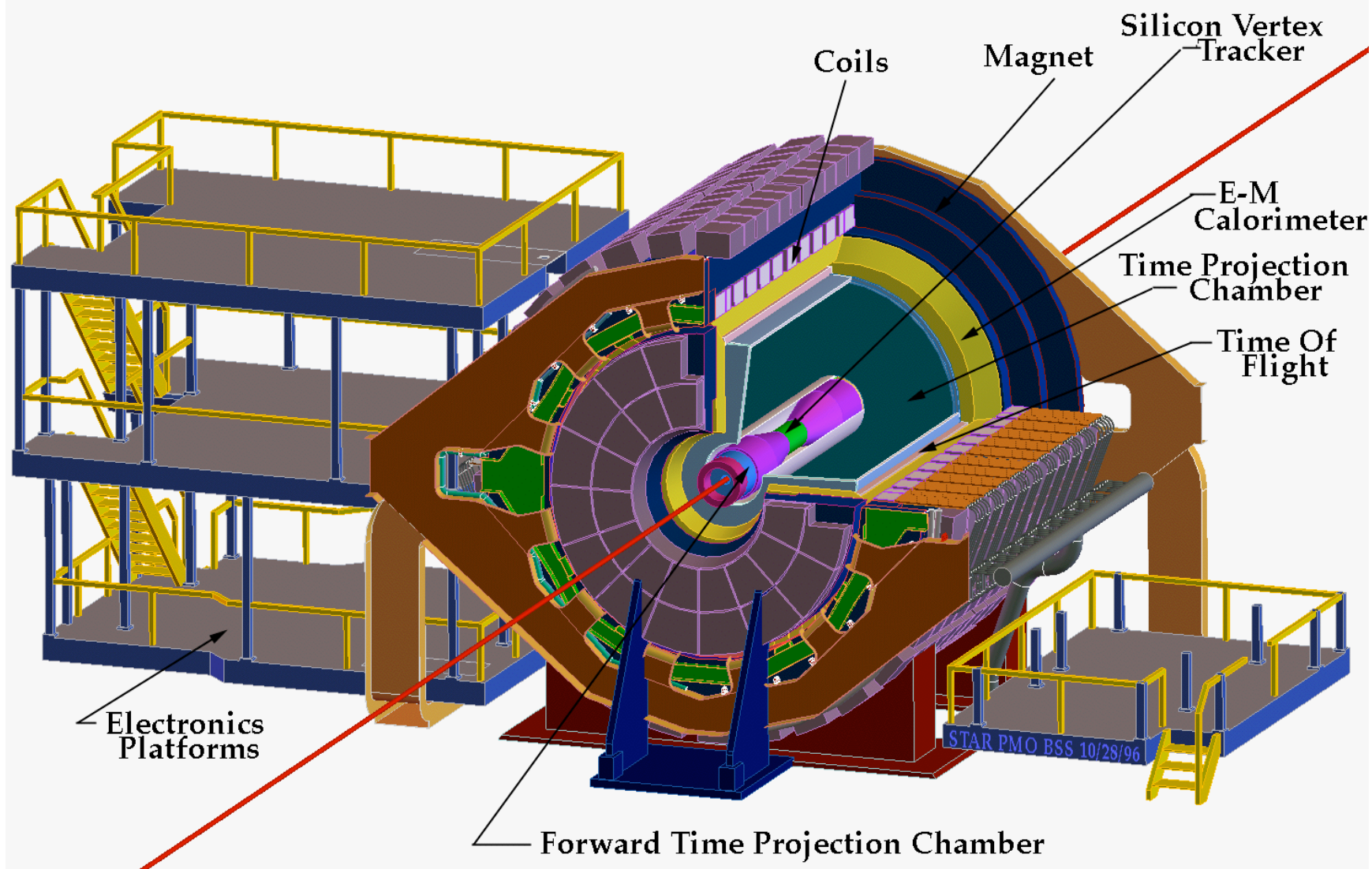


# STAR Collaboration



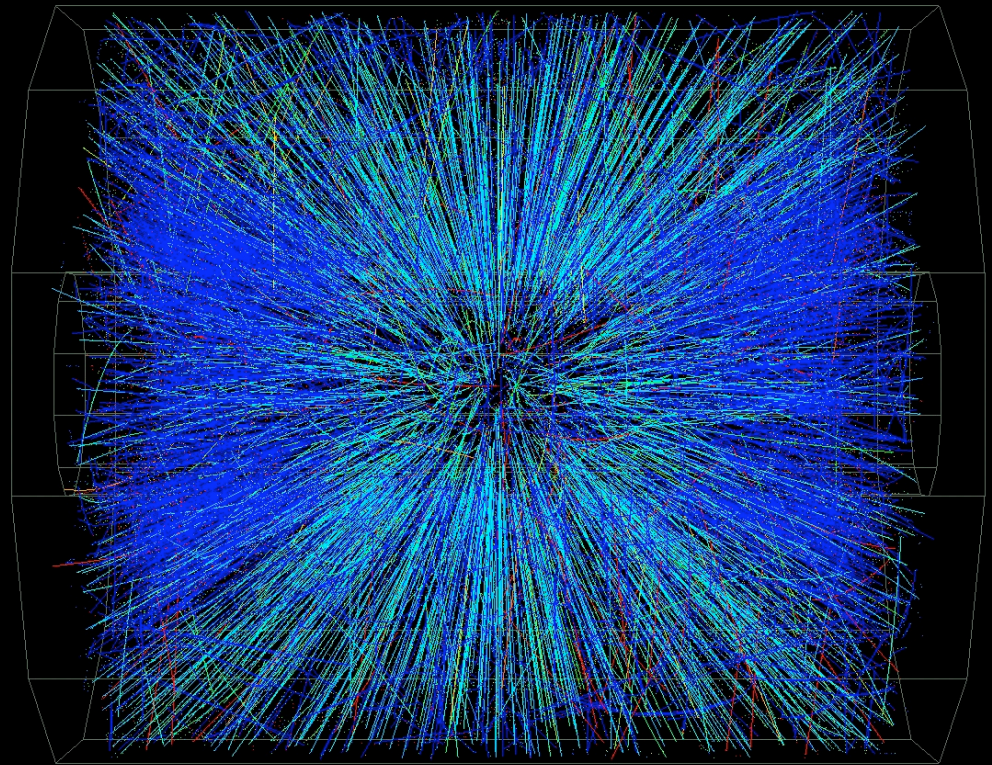
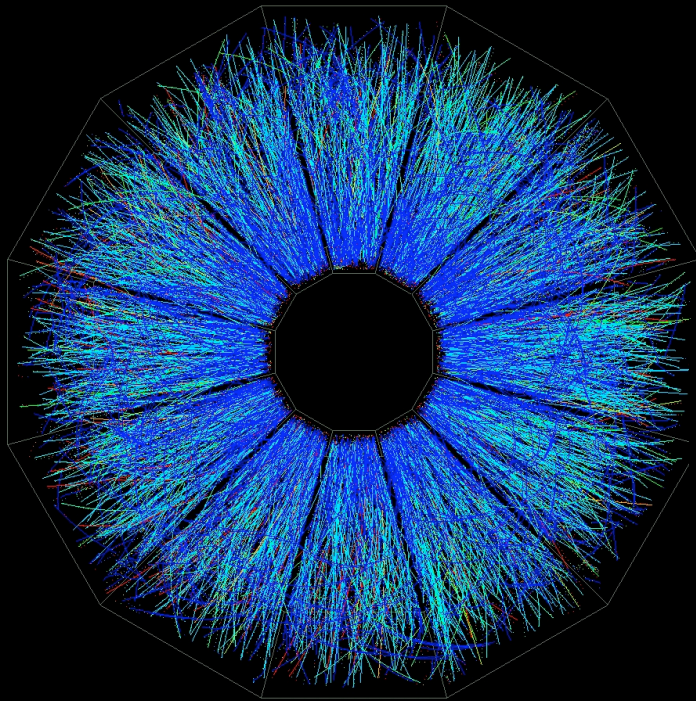


# STAR Detector



## *Au + Au Collisions at RHIC*

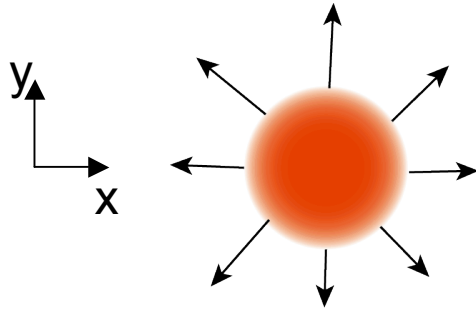
### Central Event



(real-time Level 3)

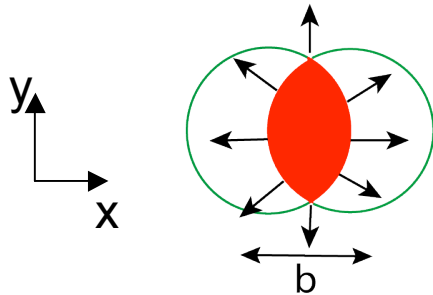


# Collective Flow



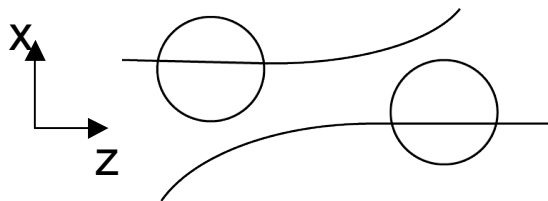
Central Collisions: transverse radial flow,  $b \sim 0$

- Integrates pressure history over complete expansion phase



Elliptic flow ( $v_2$ ), hexadecupole flow ( $v_4$ ),  $v_6, \dots$   
caused by anisotropic initial overlap region

- More weight towards early stage of expansion

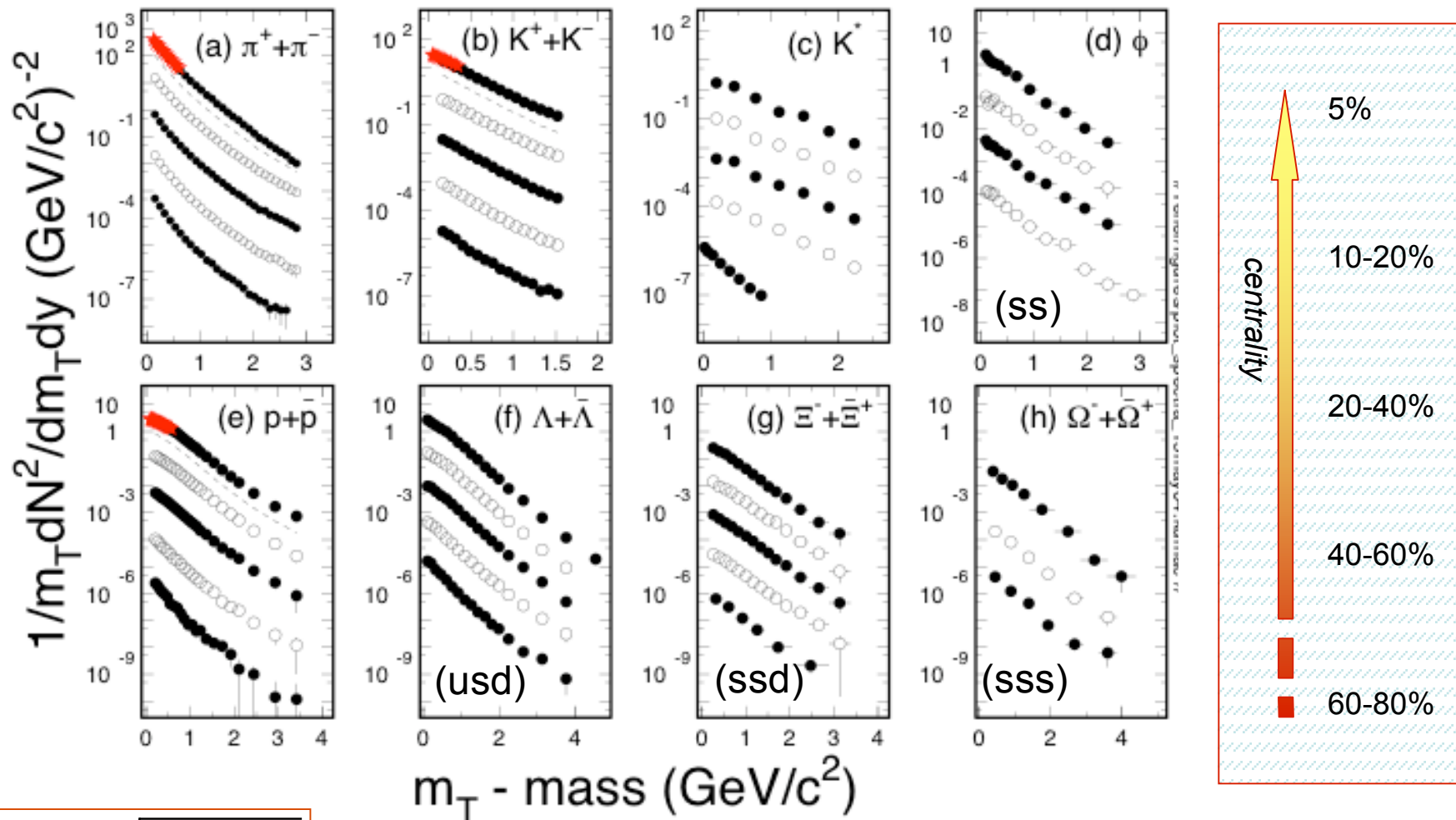


Directed flow ( $v_1$ ), sensitive to earliest collision stage ( $b > 0$ )

- Large effect at forward rapidity, at mid-rapidity perhaps different origin

# Hadron Spectra from RHIC

*mid-rapidity, p+p and Au+Au collisions at 200 GeV*



$$m_T = \sqrt{p_T^2 + m^2}$$

*Results from BRAHMS, PHENIX, and STAR experiments*

# Thermal model fit

Source is assumed to be:

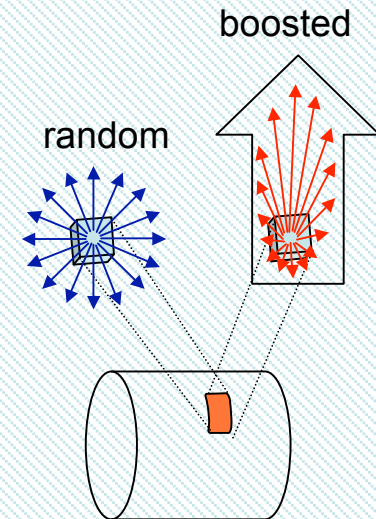
- Local thermal equilibrated  $\Rightarrow$  random motion
- Radial boosted  $\Rightarrow$  collective motion

*E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. **C48**, 2462(1993)*

$$E \frac{d^3 N}{dp^3} \propto \int_{\sigma} e^{-(u^{\mu} p_{\mu})/T_{fo}} p d\sigma_{\mu} \Rightarrow$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1 \left( \frac{m_T \cosh \rho}{T_{fo}} \right) I_0 \left( \frac{p_T \sinh \rho}{T_{fo}} \right)$$

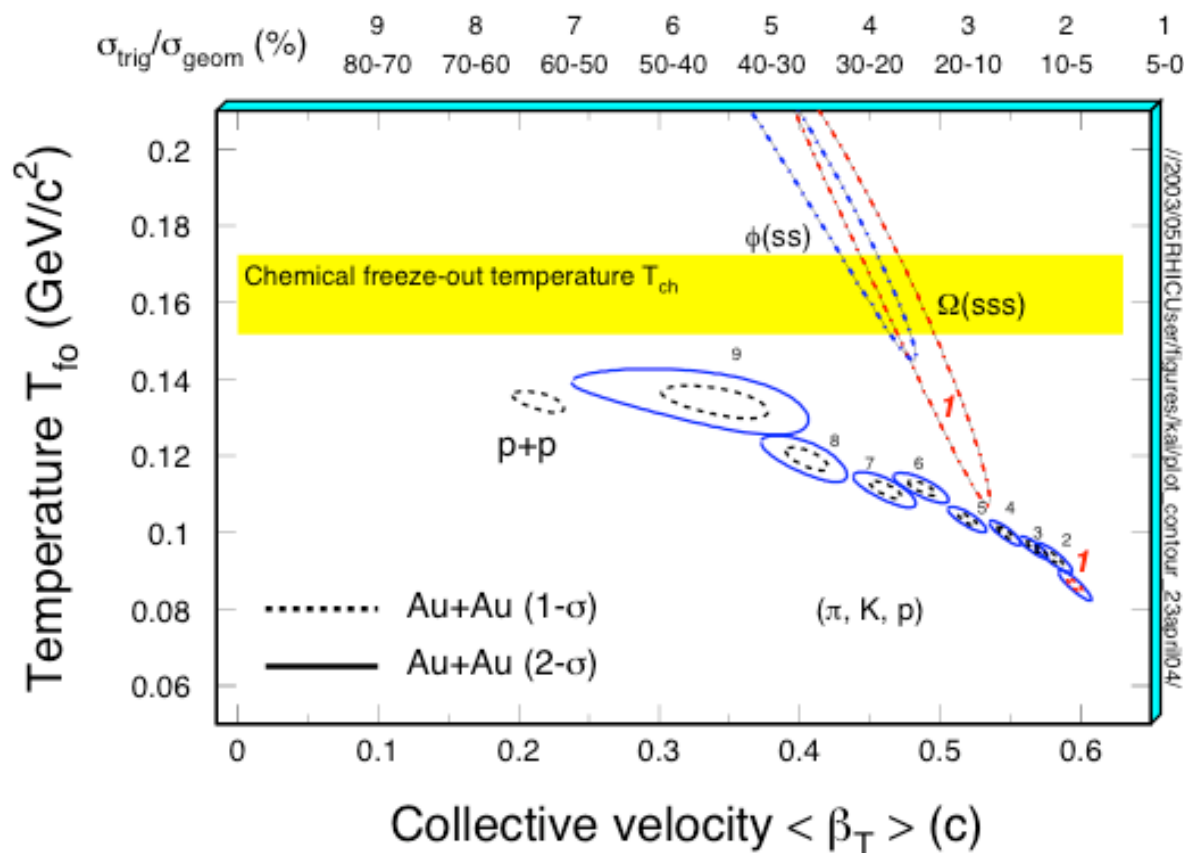
$$\rho = \tanh^{-1} \beta_r \quad \beta_r = \beta_s \left( \frac{r}{R} \right)^{\alpha} \quad \alpha = 0.5, 1, 2$$





# Fit results: $T_{fo}$ vs. $\langle \beta_T \rangle$

## 200GeV Au + Au collisions



1)  $\pi$ ,  $K$ , and  $p$  change smoothly from peripheral to central collisions.

2) At the most central collisions,  $\langle \beta_T \rangle$  reaches 0.6c.

3) Multi-strange particles  $\phi$ ,  $\Omega$  are found at higher  $T$  and lower  $\langle \beta_T \rangle$

⇒ Sensitive to early partonic stage!

⇒ How about  $v_2$ ?

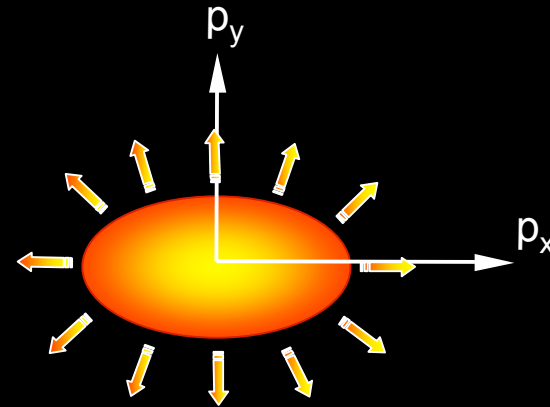
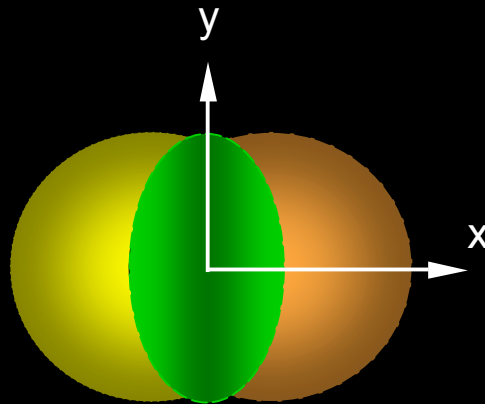
STAR: NPA715, 458c(03); PRL 92, 112301(04); 92, 182301(04).

# Anisotropy parameter $v_2$

coordinate-space-anisotropy



momentum-space-anisotropy



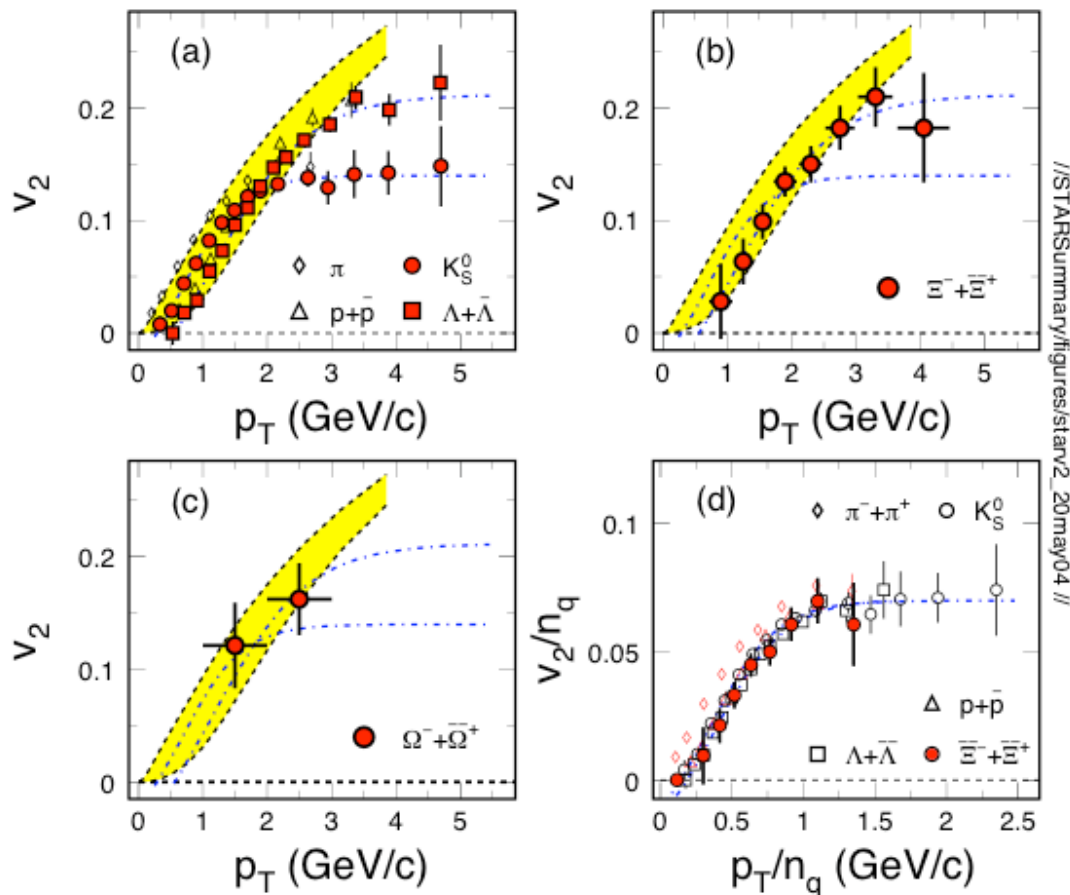
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

**Initial/final conditions, EoS, degrees of freedom**

# Collectivity, deconfinement at RHIC

## 200GeV Au + Au collisions



- $v_2$ , spectra of light hadrons and multi-strange hadrons
- scaling of the number of constituent quarks

At RHIC, I believe we have achieved:

⇒ **Partonic Collectivity**

⇒ **Deconfinement**

*PHENIX*: PRL**91**, 182301(03)

*STAR*: PRL**92**, 052302(04)

S. Voloshin, NPA**715**, 379(03)

Models: Greco et al, PRC**68**, 034904(03)

X. Dong, et al., Phys. Lett. **B597**, 328(04).

....

# Summary I

- Flavor equilibration - necessary for QGP
- Jet energy loss - **QCD** at work
- Collectivity - pressure gradient  $\partial P_{QCD}$   
Deconfinement and Partonic collectivity
- **Next step:** demonstrate the status of possible thermalization (**T**) in Au+Au collisions at RHIC  
⇒ heavy-flavors (c- & b-quarks) collectivity

## II. Neutrino-less double beta decay

# 1930 - W. Pauli and $\nu$



Public letter to the group of the Radioactives at the district society meeting in Tübingen:  
Physikalisches Institut  
der Eidg. Technischen Hochschule  
Gloriastr.  
Zürich

Zürich, 4 December 1930

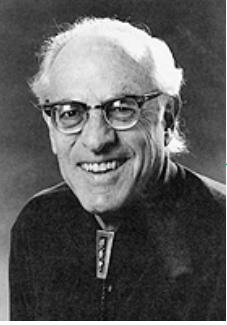
“As the bearer of these lines, to whom I graciously ask to listen, will explain to you in more detail, how because of the ‘wrong’ statistics of the N and  ${}^6\text{Li}$  nuclei and the continuous beta-spectrum. I have hit upon a desperate remedy to save the ‘exchange theorem’ of statistics and the law of conservation of energy. ***Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have the spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.*** – The continuous beta-spectrum would then become understandable by the assumption that in beta-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

....

I admit that on a first look my way out might seem to be quite unlikely, since one would certainly have seen the neutrons by now if they existed. But nothing ventured nothing gained, and the seriousness of the matter with the continuous beta-spectrum is illustrated by a quotation of my honored predecessor in office. Mr. Debye, who recently told me in Brussels: ‘Oh, it is best not to think about it, like the new taxes.’ Therefore one should earnestly discuss each way of salvation. – So, dear Radioactives, examine and judge it. – Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zurich because of a ball on the night of 6/7 December. – With my best regards to you, and also Mr. Back, your humble servant.”

W. Pauli





# 1956, $\bar{\nu}_e$ discovered

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Twenty six years later, in 1956, Reines and Cowan first observed the electron anti- $\nu$ .

Today, after seventy five years of Pauli's prediction, fundamental properties of neutrino remain to be mysteries:

- neutrino and its anti-particle
- neutrino mass
- in SM, the knowledge of our understand of the Nature,  $m_\nu = 0$

Consequences:

- Inside: the structure and symmetry of elementary particles
- Outside: the beginning and evolution of our universe

# $\nu$ -oscillation results

- |                 |  |
|-----------------|--|
| 1) Solar:       | Homestake, Kamiokande, SAGE<br>GALLEX/GNO, SK, SNO |
| 2) Atmospheric: | SK, SNO  |
| 3) Reactor:     | KamLAND  |

$$\Delta m_{1,2}^2 = (7.2 \pm 0.7) * 10^{-5} eV^2$$

$$\Delta m_{i,j}^2 = m_j^2 - m_i^2$$

$$|\Delta m_{2,3}^2| = (2.0 \pm 0.4) * 10^{-3} eV^2$$

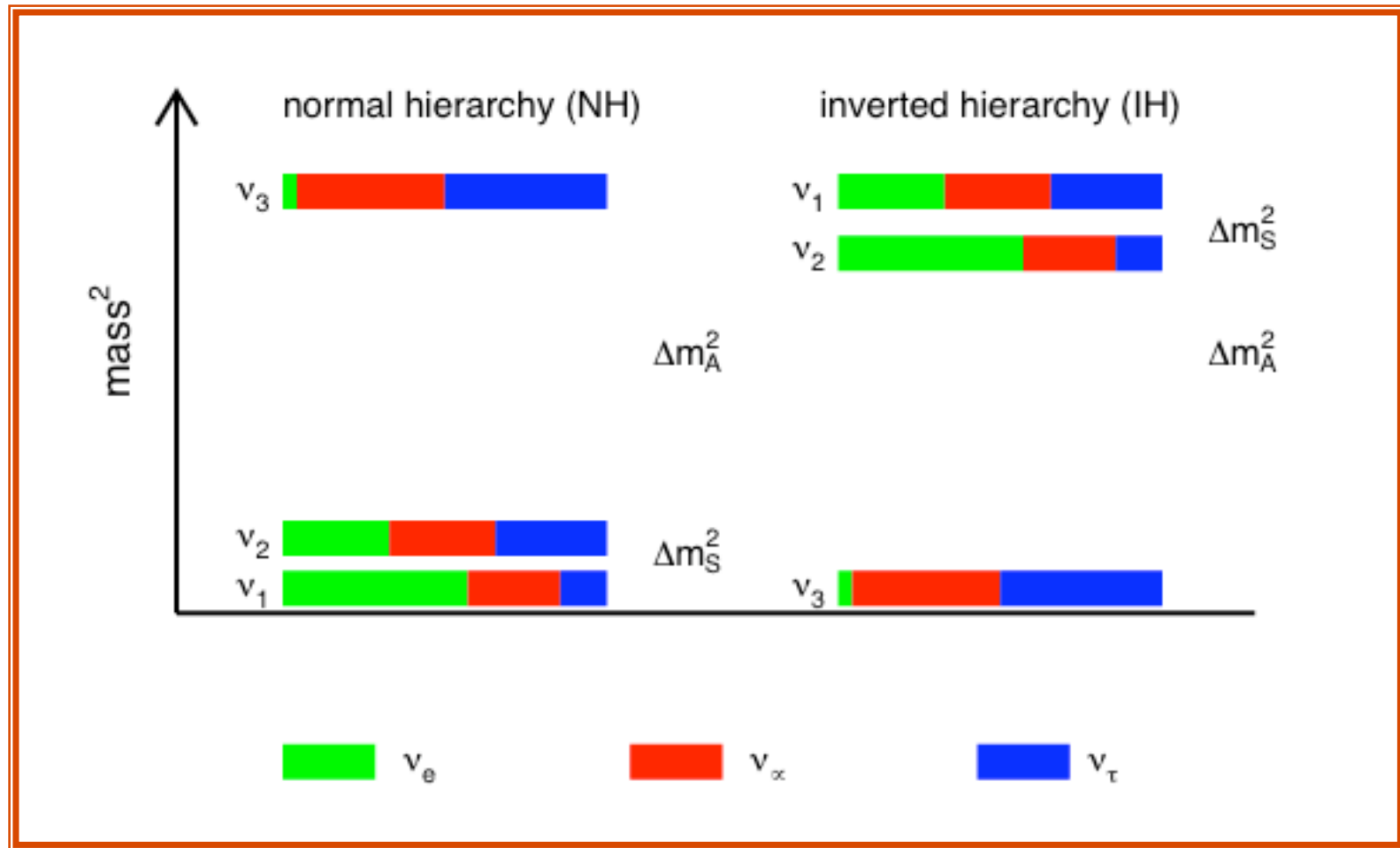
$$\tan^2 \theta_{1,2} = 0.44 \pm 0.05$$

$$\sin^2 2\theta_{2,3} = 1.00 \pm 0.04$$

$$\sin^2 2\theta_{1,3} = 0.000 \pm 0.085$$

*F. Feruglio, A. Strumia, and F. Vissani, Nucl. Phys. **B637**, 345(02); **B659**, 359(03)*

# $\nu$ -oscillation results



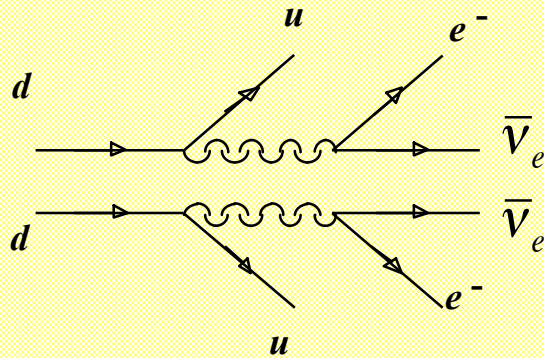
- B. Pontecorvo, *Zh. Eksp., Teor. Fiz.* **33**, 54(57); **34**, 247(1958)
- Z. Maki, M. Nakagawa, and S. Sakata, *Prog. Theor. Phys.*, **28**, 870 (1962)



# Double beta decay



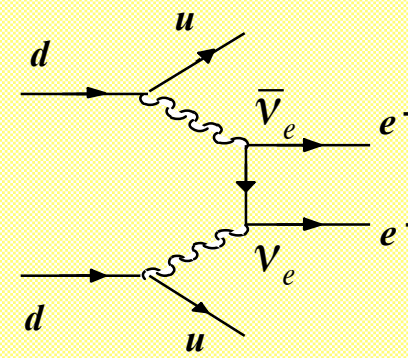
Fotografia di Ettore Majorana tratta dalla tessera universitaria datata 3 novembre 1933



$$\nu_f \neq \bar{\nu}_f$$

Dirac type

$2\nu 2\beta$  decay



$$\nu_f = \bar{\nu}_f$$

Majorana type

$0\nu 2\beta$  decay



# Neutrino's nature ?

In oscillation experiment, only the mass<sup>2</sup> differences are determined which means neutrinos have finite mass. We need to know the nature of neutrino and their masses.

$$\nu_i \neq \bar{\nu}_i$$

Dirac type

$$\nu_i = \bar{\nu}_i$$

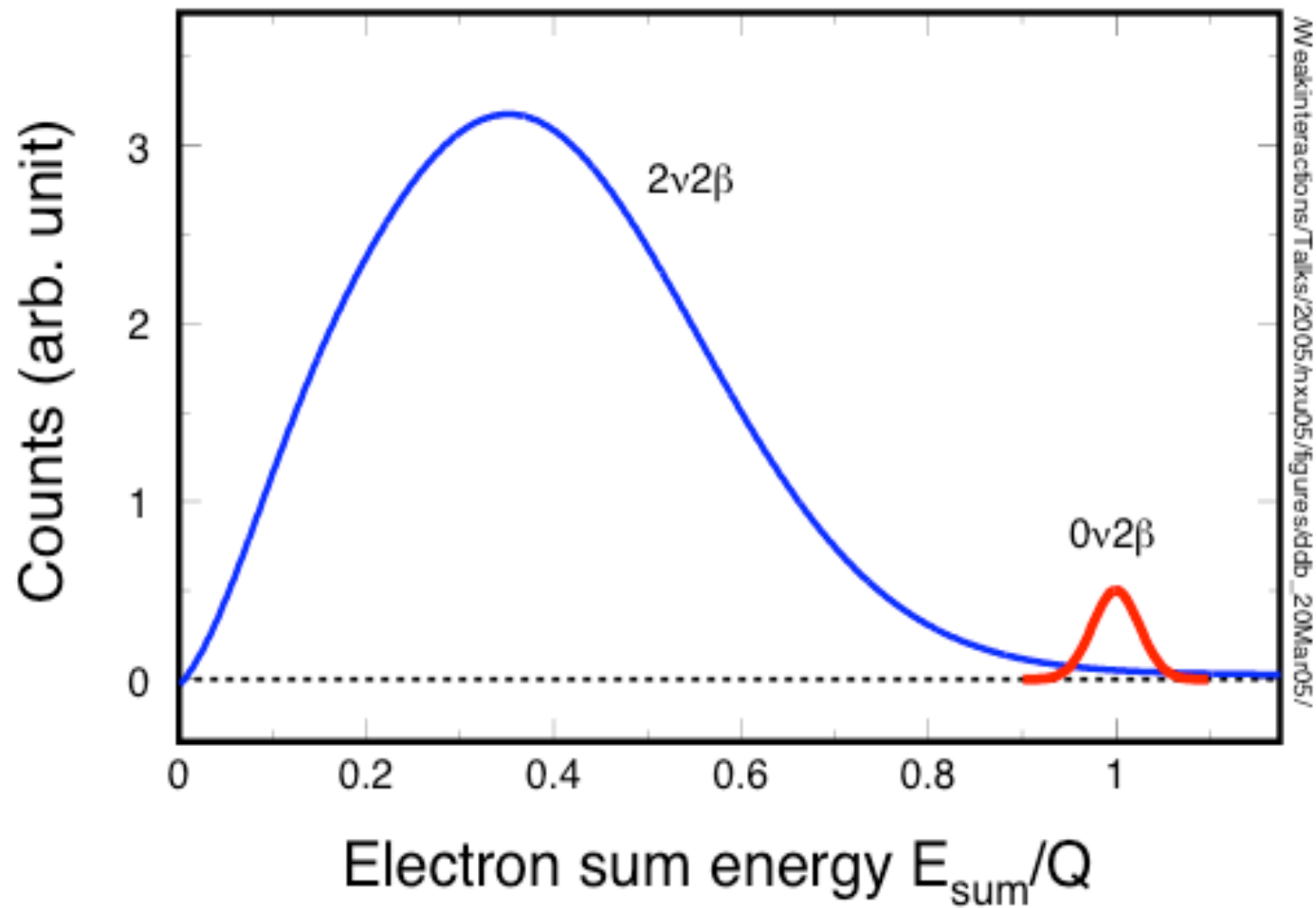
Majorana type

Lepton # conservation violated

Beyond SM

Experiment:    neutrino-less double beta decay  
                      neutrino - neutrino interferometry\* (?)

# Double beta decay





# Experimental methods

Fermi's golden rule

Measurements

Phase space integral

Neutrino mass

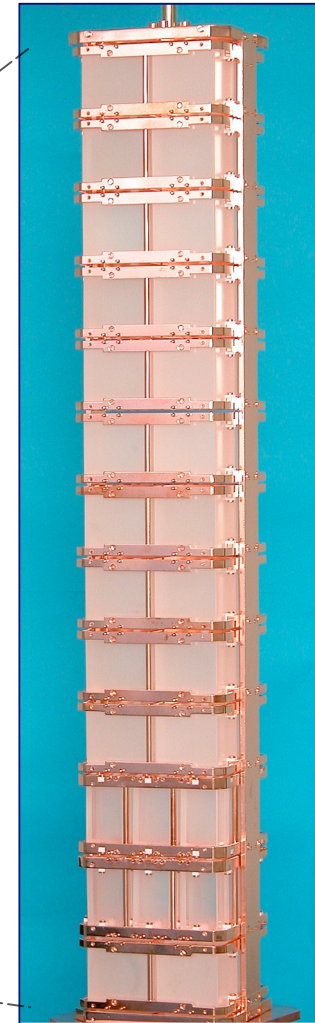
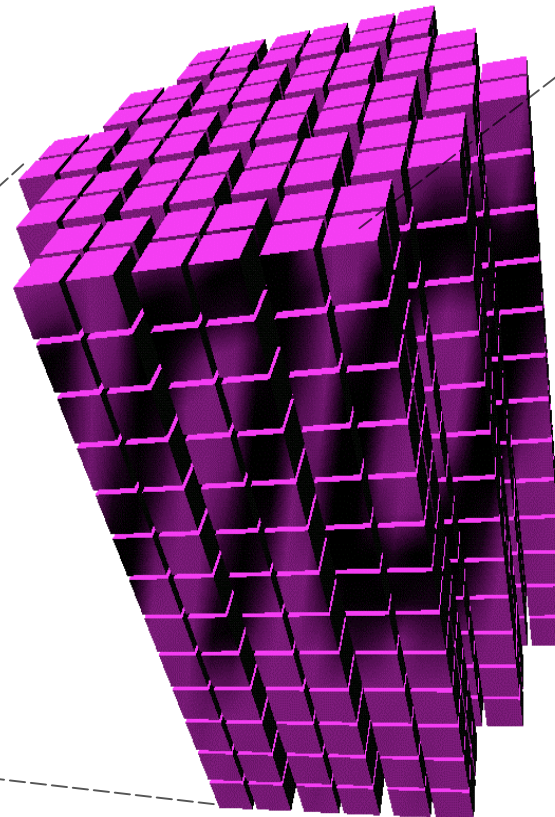
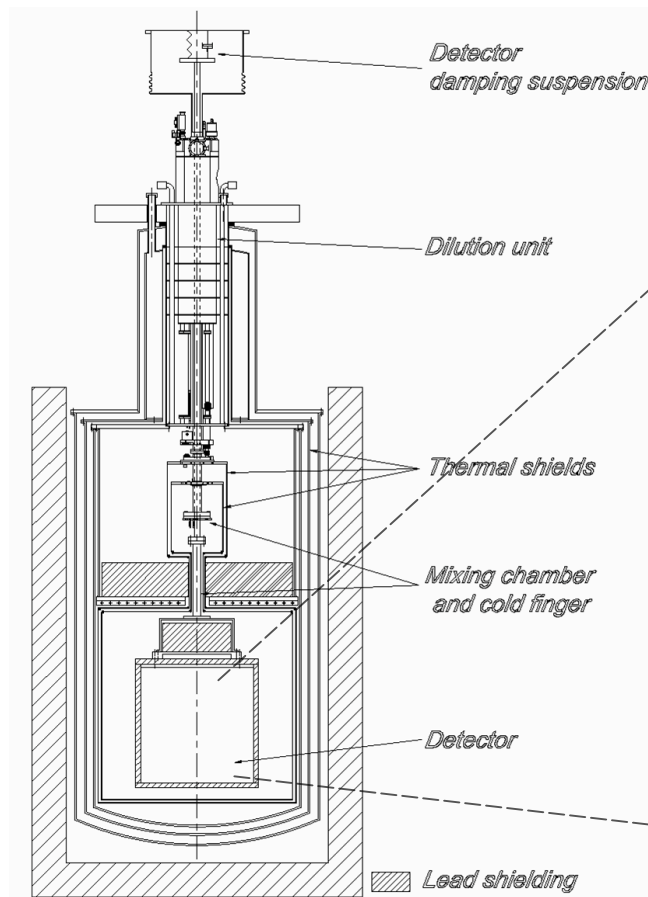
$$\left[ T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu} * \left| M^{0\nu} \right|^2 * \langle m_\nu \rangle^2$$

Nuclear decay matrix elements  
Large model uncertainties

# CUORE/CUORICINO



CUORE starts data taking in 2009  
<http://crio.mib.infn.it/wig/Cuorepage/CUORE.php>

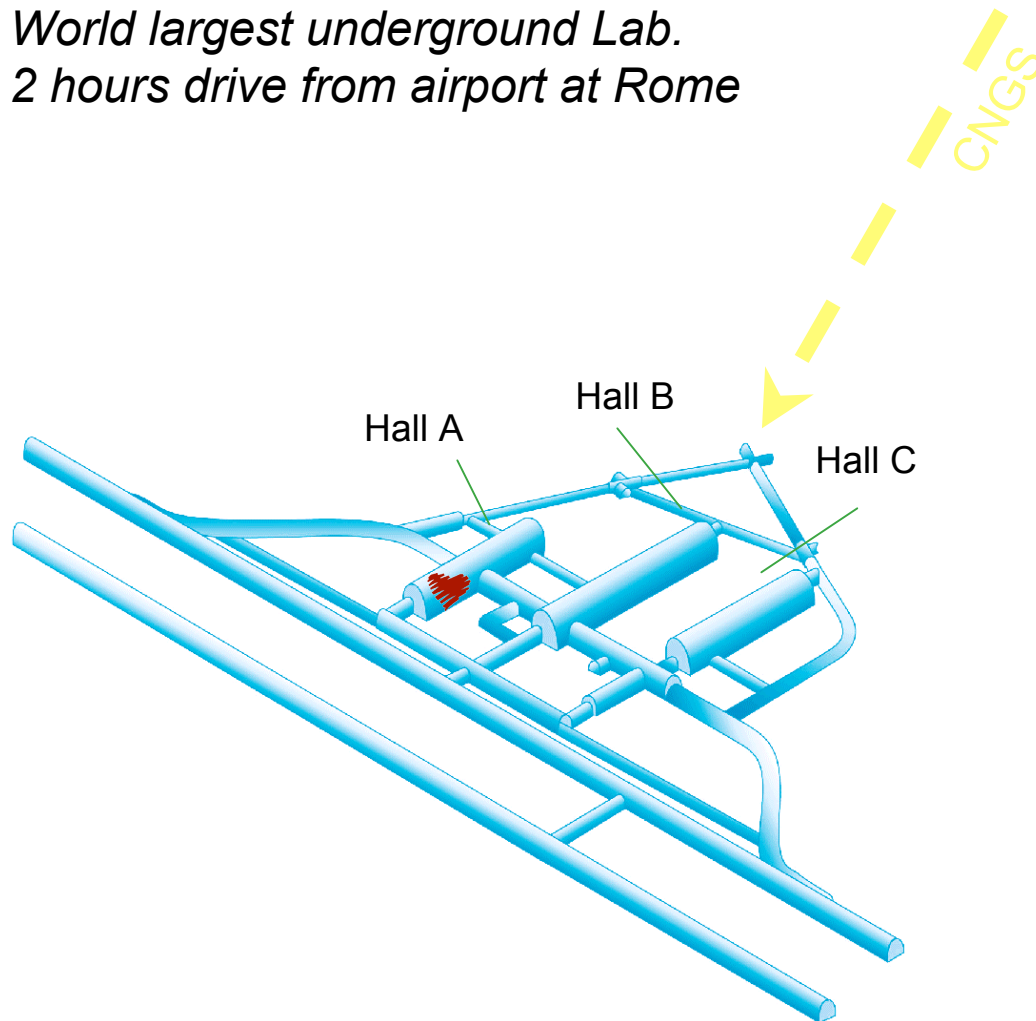


Details see: Tom Gutierrez et al. talk

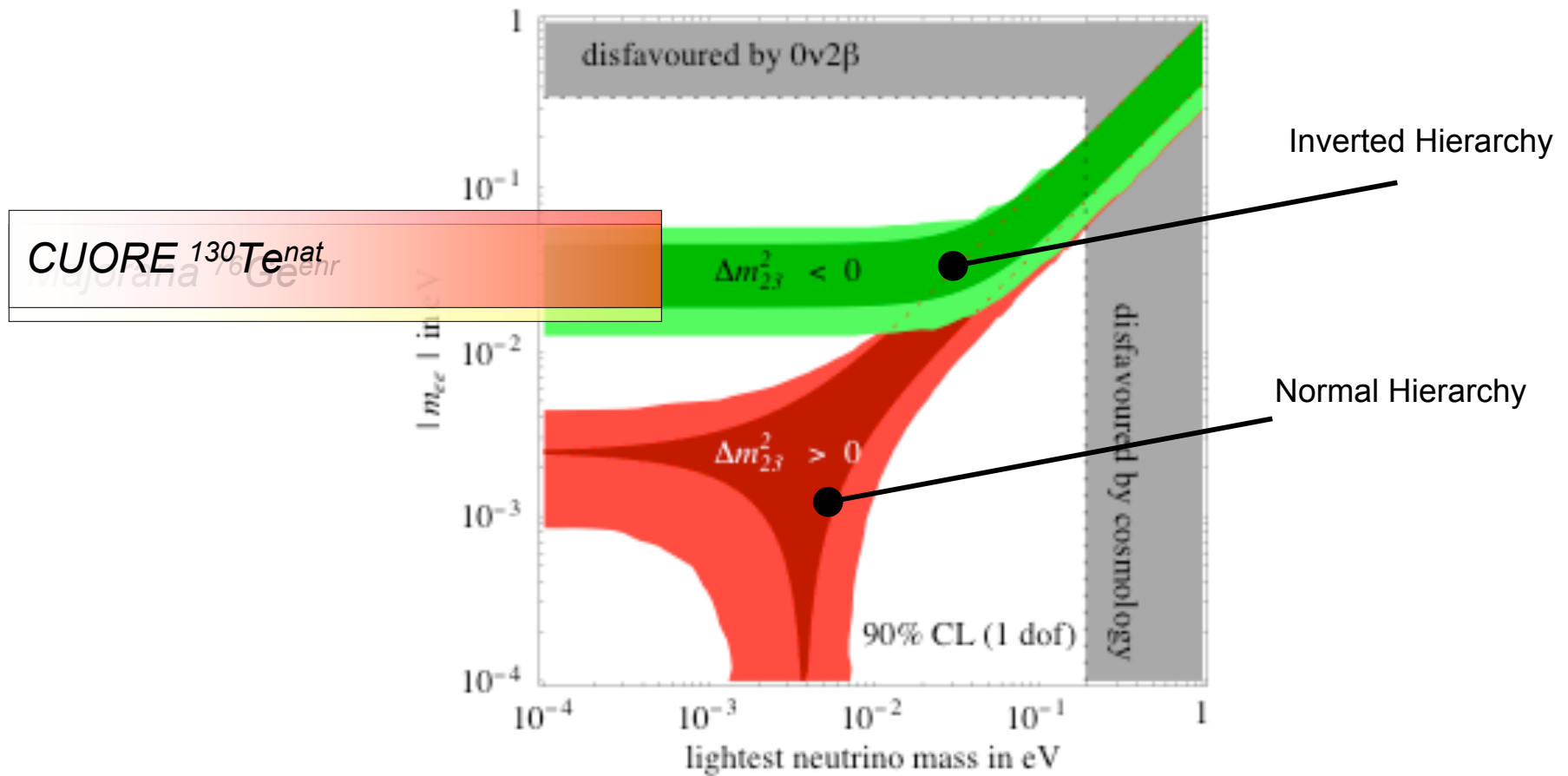


# Laboratori Nazionali Del Gran Sasso (LNGS)

- *World largest underground Lab.*
- *2 hours drive from airport at Rome*



# Next generation $0\nu 2\beta$ experiments



F. Feruglio, A. Strumia, and F. Vissani, *Nucl. Phys.* **B637**, 345(02); **B659**, 359(03)



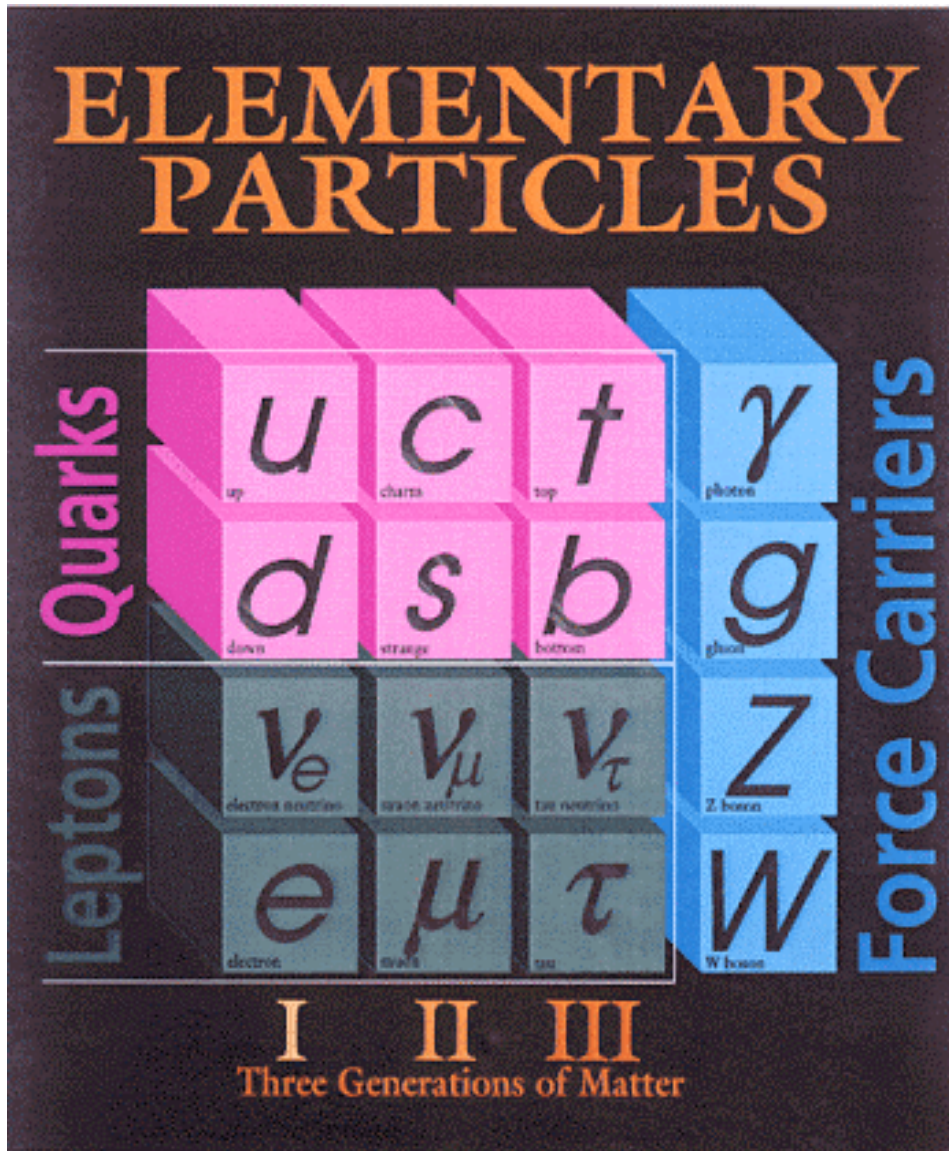
# Summary II

Next generation  $0\nu 2\beta$  experiments potentials:

- Rule out inverted hierarchy scenario, based on today's model limit.
- Discover neutrino nature.
- Determine neutrino mass.



# “Standard” Model



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# The fate of Spinosaurid ...

P.C. Sereno *et al.* **Science**, Nov. 13, 1298(1998).  
(Spinosaurid)



For about 50 years Spinosaurid has been vegetarian, now it is a carnivore.  
**Imagine** what will it be in the next 50 years, 100 years, ...?



# What can you do?

## **High-Energy Nuclear Collisions:** (RHIC at BNL, Long Island, NY)

- 1) Analyze data from 200 GeV Au+Au collisions;
- 2) Simulations, construction new detector - heavy flavor tracker

...

SoftHadron Group: 3.5 Staffs, 3 postdocs, 5 Ph.D students

<http://www-rnc.lbl.gov/~nxu/group/starhadron.html>

## **Neutrino-less Double Beta Decay:** (CUORE at Gran Sasso, Italy)

- 1) Analyze data from CUORICINO;
- 2) Simulations, proposal for construction new detector CUORE

...

CUORE group: 2.5 staffs, 1.5 postdocs, 1 Ph.D student (?)

[http://www-rnc.lbl.gov/~nxu/cuore/cuore\\_lbnl.html](http://www-rnc.lbl.gov/~nxu/cuore/cuore_lbnl.html)

A new group, needs more students!





# Acknowledgements

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X. Dong\*, H. Huang, P. Jacobs, H.G. Ritter, K. Schweda\*, A. Tai, Z. Xu  
*E.L. Bratkovskaya*, L. Grandchamp, J. Raufeisen, R. Vogt, X.N. Wang

I. Bandac, C. Bucci, S. Freeman, P. Gorla, T. Gutierrez\*, J. Thomas, F. Vassani